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HEAD-TAIL INSTABILITY AT TEVATRON

EXPERIMENTAL STUDIES

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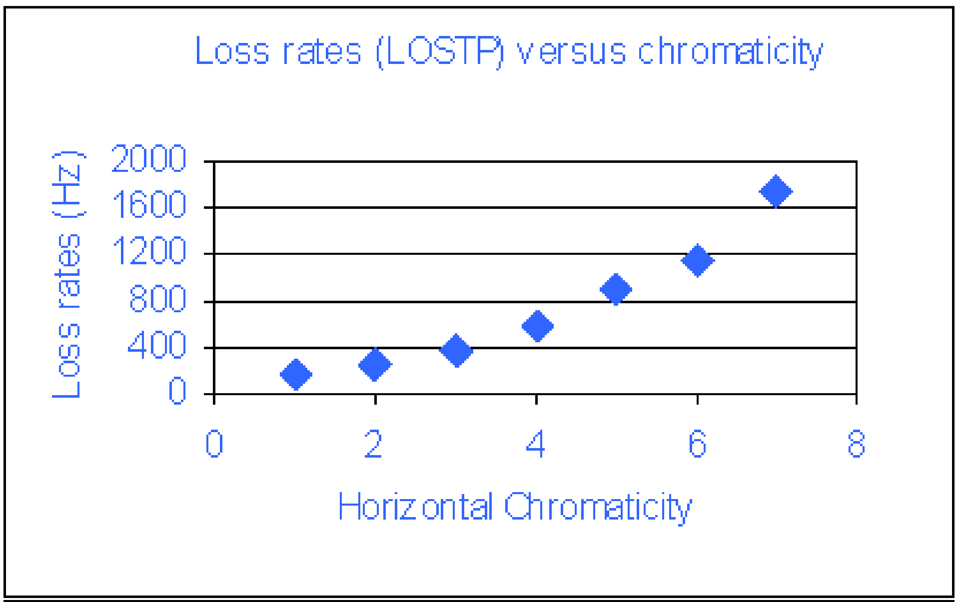
FERMILAB, July 2, 2003

THE CONTENTS OF A TALK

INTRODUCTION

Experimental observations and theoretical examination allow identifying the Tevatron transverse instability as a weak head-tail, driven by the short-range wake fields induced by the resistive wall impedance in presence of space charge. It is a single bunch effect.

In order to prevent developing this instability, the lattice chromaticities are set as high as $\xi_{x,y}\cong+8$ at E=150 GeV and $\xi_{x,y}\cong+26$ at the collision energy that results in a degradation of the dynamic aperture and reduction of beam lifetime.

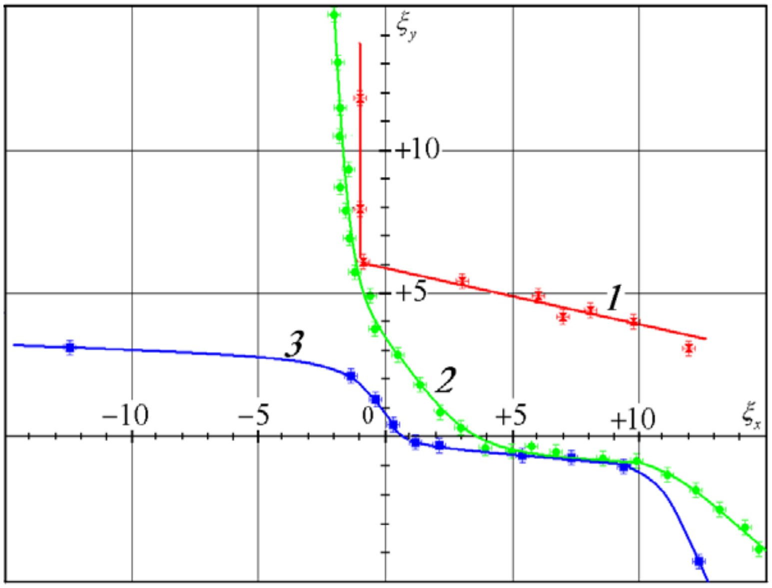


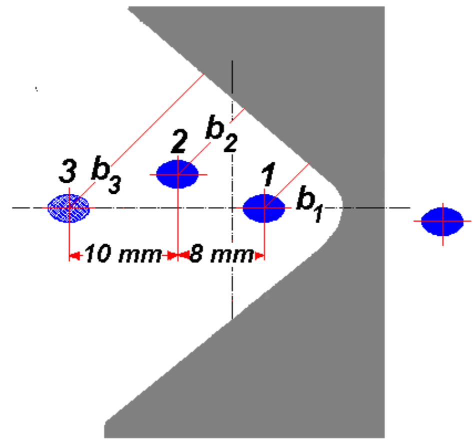
The widths of the chromatic betatron tune spreads are proportional to the chromaticities: $\Delta\nu_{x,y}=2|\xi_{x,y}\cdot\Delta p/p|$. Observation of the particle losses by monitors around the CDF-detector demonstrates the similar correlation with the absolute value of chromaticity with minimum at $\xi_{x,y}\cong 0$.

At first, A. Burov suggested it and then the experimental beam studies have shown that a major source of the Tevatron transverse impedance is the Lambertson injection magnet, having high resistivity due to the bare laminations.

Decreasing the transverse impedance by insertion of a thin shielding liner inside the magnet in combination with introducing Landau damping by octupoles will promote stabilization of the coherent head-tail modes at zero chromaticity range. As a result, the colliding beam intensities can be increased that will promote enhancement of peak and integrated luminosity.

STABILITY REGIONS OF THE HEAD-TAIL MODES IN THE CHROMATICITY SPACE





All measurements are performed with single proton bunches $N_{ppb}=2.6*10^{11}$. The thresholds of the excitation correspond to an increase in the coherent component of Schottky spectrum, as the chromaticities were smooth decreased.

1. Injection orbit (curve 1): $b_1 \approx 6\ mm$,;

Stability region is limited by excitation of the quadrupole mode with longitudinal number ***l=2*** in vertical plane at ξ_y**>0** and horizontal coherent mode with ***l=0*** when ξ_x**~-1**.

The stability bounds for the vertical and horizontal modes are in principle different. A possible reason could be related to the space charge tune shifts, which are different for the two planes because of dispersion. The vertical incoherent shift is two times larger than the horizontal shift. Calculated coherent tune shifts for the first two horizontal higher order modes are found to be comparable with the incoherent space-charge tune shift that promotes Landau damping due to a synchrotron tune spread.

2. Central regular orbit (curve 2): $b_2 \approx 9\ mm$

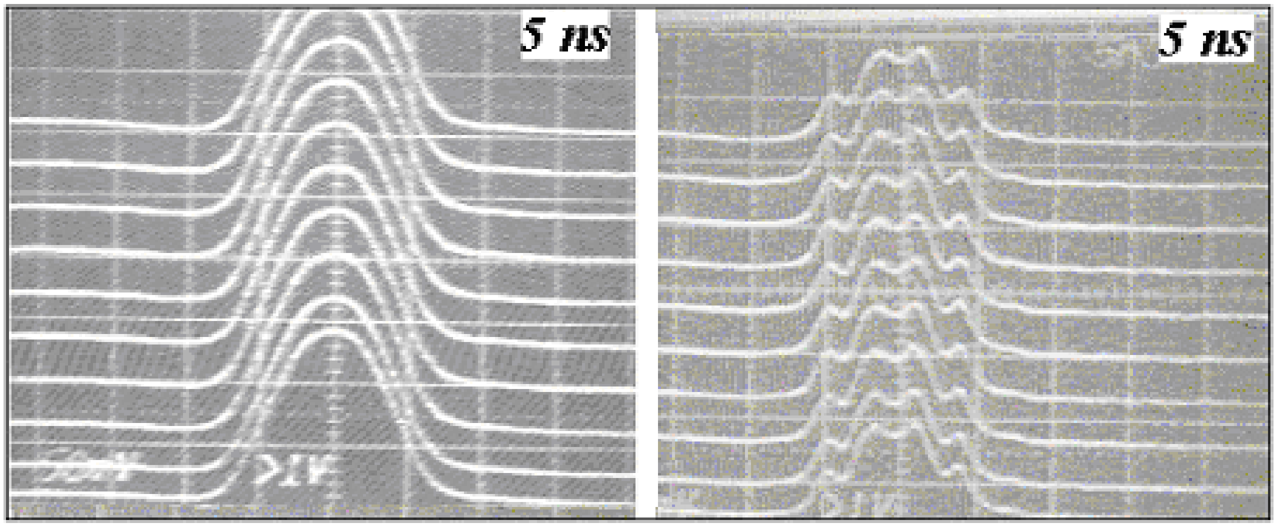
A single vertical mode with dipole longitudinal configuration ***l=1*** is observed at the chromaticity threshold $\xi_y \leq 3$. The horizontal higher order head-tail modes are stable out of the coupling resonance.

3. Local orbit bump 3 (curve 3): $b_3 \approx 18\ mm$, $\Delta Y = -3\ mm$, $\Delta X = -10\ mm$

Coherent modes with monopole longitudinal configuration are unstable at ξ_y**<0,** ξ_x**<0**

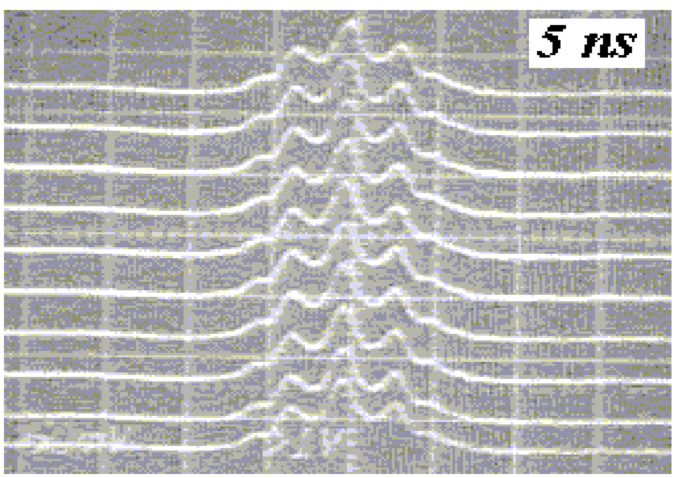
Similar stability conditions are expected after installation of the planned shielding of the Lambertson magnet bare laminations.

OBSERVATIONS BY RESISTIVE WALL MONITOR



N_{ppb}=2.6 $*10^{11}$ (Initial beam) $\Rightarrow$ N_{ppb}=1.03 $*10^{11}$ (Remaining beam)

Longitudinal density profiles of the initial and remaining proton bunches before and after self-stabilization of the vertical instability due to the particle losses. The particles were lost due to an transverse aperture limit in accordance with the longitudinal configuration of the coherent vertical oscillations that points qualitatively at excitation of the head-tail mode with ***l=2* (**quadrupole mode**).**

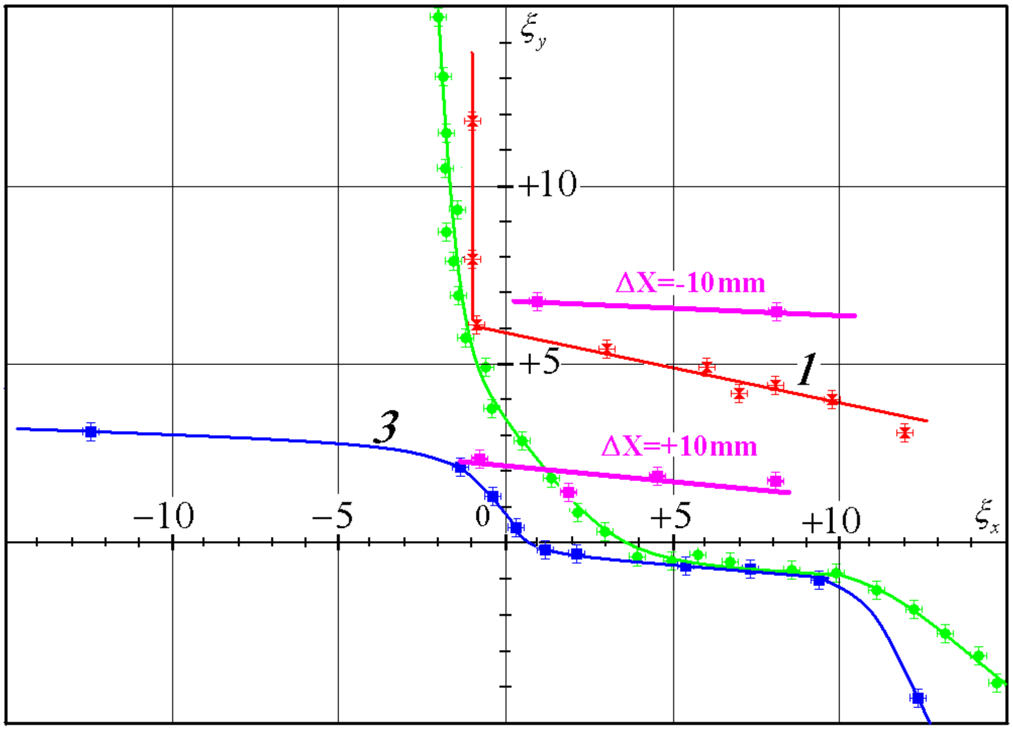


$\xi_x \approx +5.5$, $\xi_y \approx +2.7$

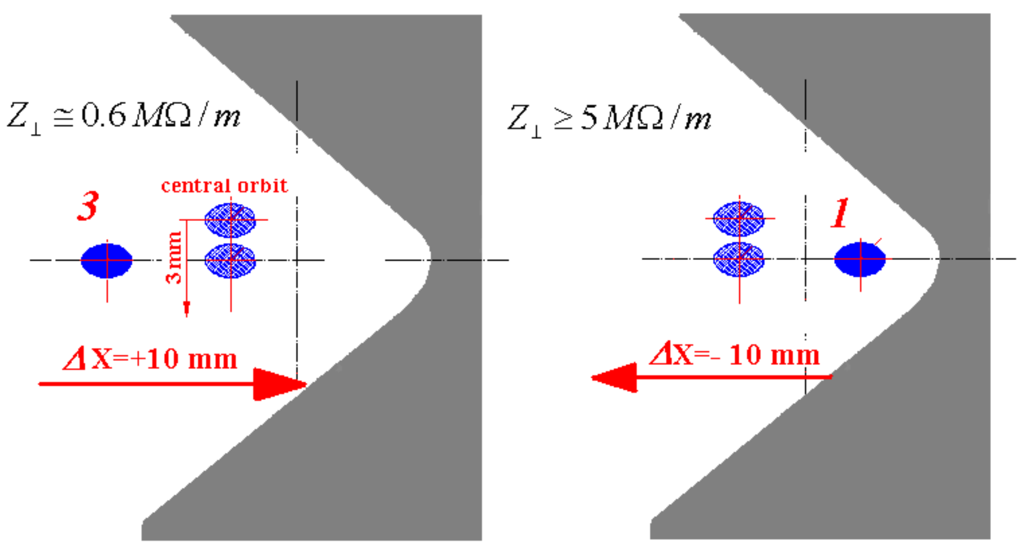
Combination of the head-tail modes with ***l=1* (dipole mode)** and ***l=3*(sextupole mode)**

N_{ppb}=2.6 $*10^{11}$ (Initial beam) $\Rightarrow$ N_{ppb}=0.7 $*10^{11}$ (Remaining beam)

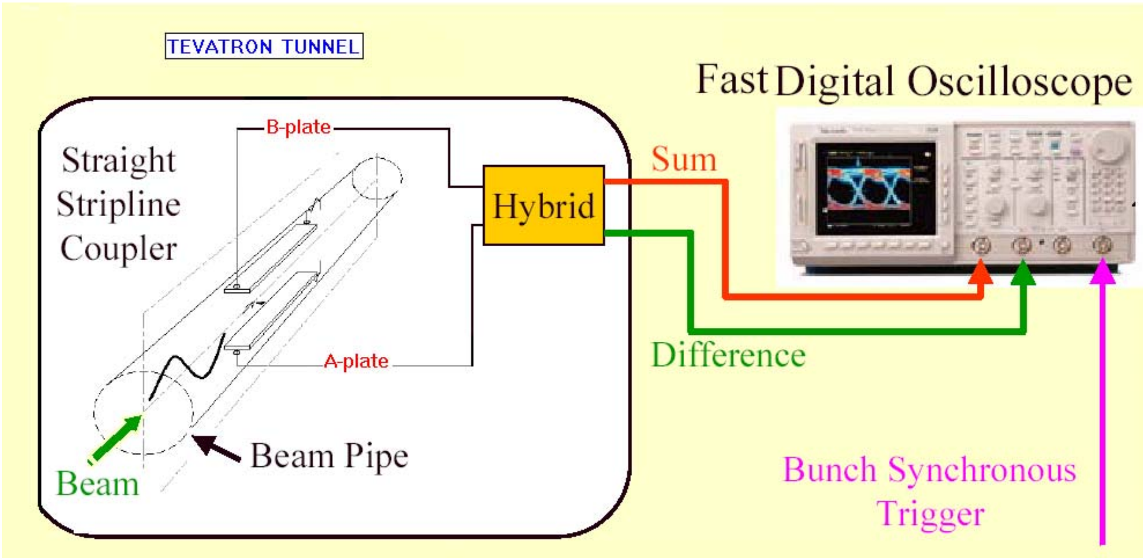
HEAD-TAIL STABILITY REGIONS FOR THE TWO F0-LAMBERTSON MAGNET OFFSETS



Instability observation clearly has shown that the beam orbit shift inside the Lambertson magnet aperture leads to qualitative changes in the stability condition for coherent head-tail modes. This fact strongly points at a dominant contribution of the magnet to the impedance budget.



TURN-BY-TURN MEASUREMENT TECHNIQUE



A fast digital oscilloscope, connected to the horizontal and vertical 1-meter long strip-line pickups, records turn-by-turn data for 2000 turns. Each turn data are sampled during 80 ns with 0.4 ns rate so that the transverse head-tail dynamics of single bunch could be observed. After the measurement, the signals are deconvoluted and transverse positions along the bunch are computed. The measurements are synchronized with the beam injection. At the injection orbit bump, the coherent tune shifts and growth rates were measured with the turn-by-turn monitor system at injections of single proton bunches.

Longitudinal configuration of the dipole moment transverse oscillations can be measured as:

$$\bar{Y}(n,\tau) = \frac{A}{2} \cdot \frac{Difference[A(n,\tau) - B(n,\tau)]}{Sum[A(n,\tau) + B(n,\tau)]}$$

Developing of head-tail instability at different chromaticities for single coalesced proton bunch after injection into Tevatron

Longitudinal and transverse dampers are OFF

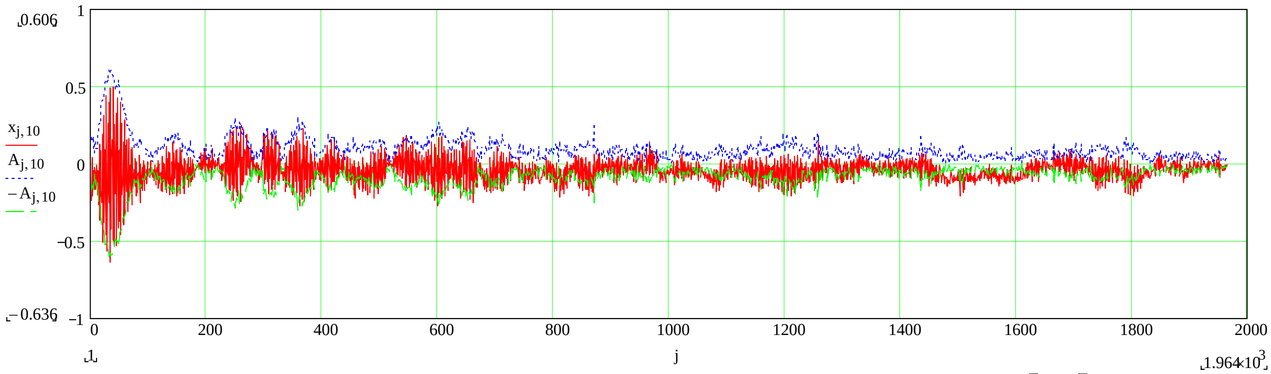


Fig.1. No instability. $N \approx 2.6 \cdot 10^{11}, \xi_x \approx 8, \xi_y \approx 2, [\nu_x] = 0.5850, [\nu_y] = 0.5736$

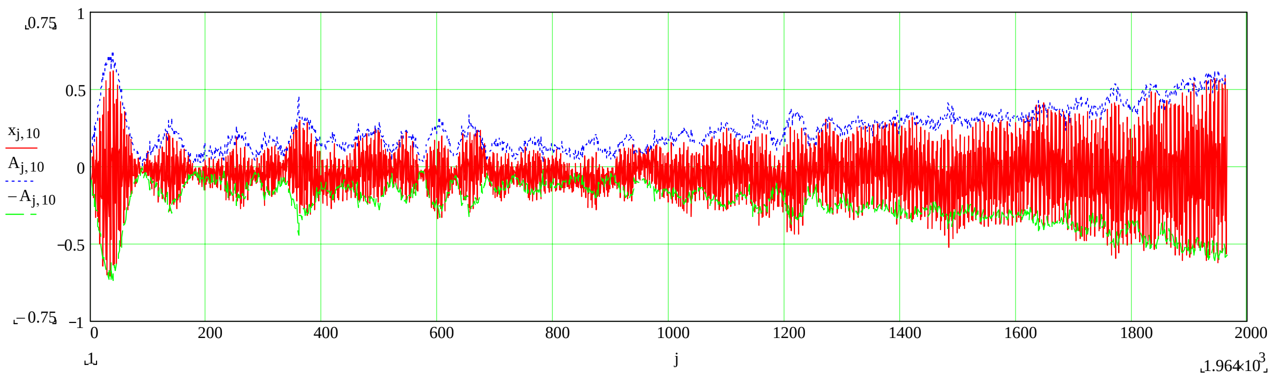


Fig.2 Developing of the coherent head-tail mode with dipole longitudinal configuration

$$N \approx 2.6 \cdot 10^{11}, \xi_x \approx 6, \xi_y \approx 2, [\nu_x] = 0.5848, [\nu_y] = 0.5721$$

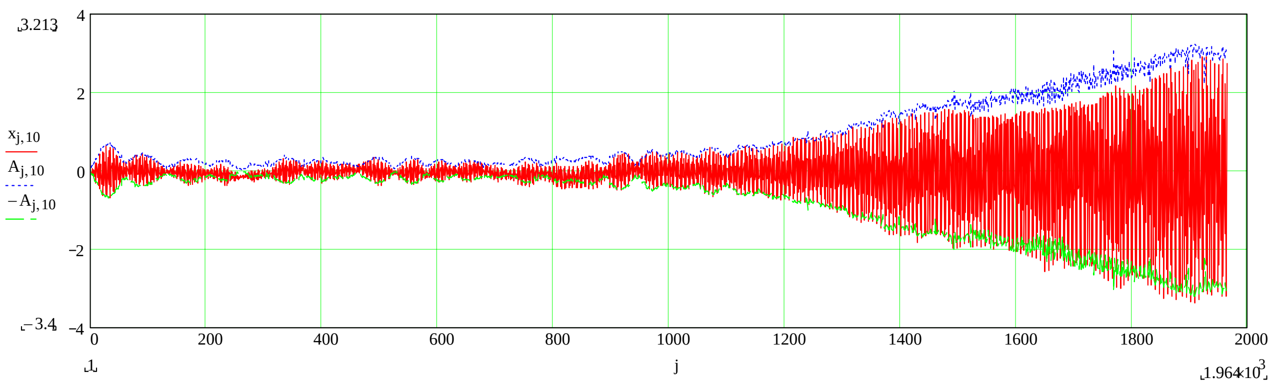
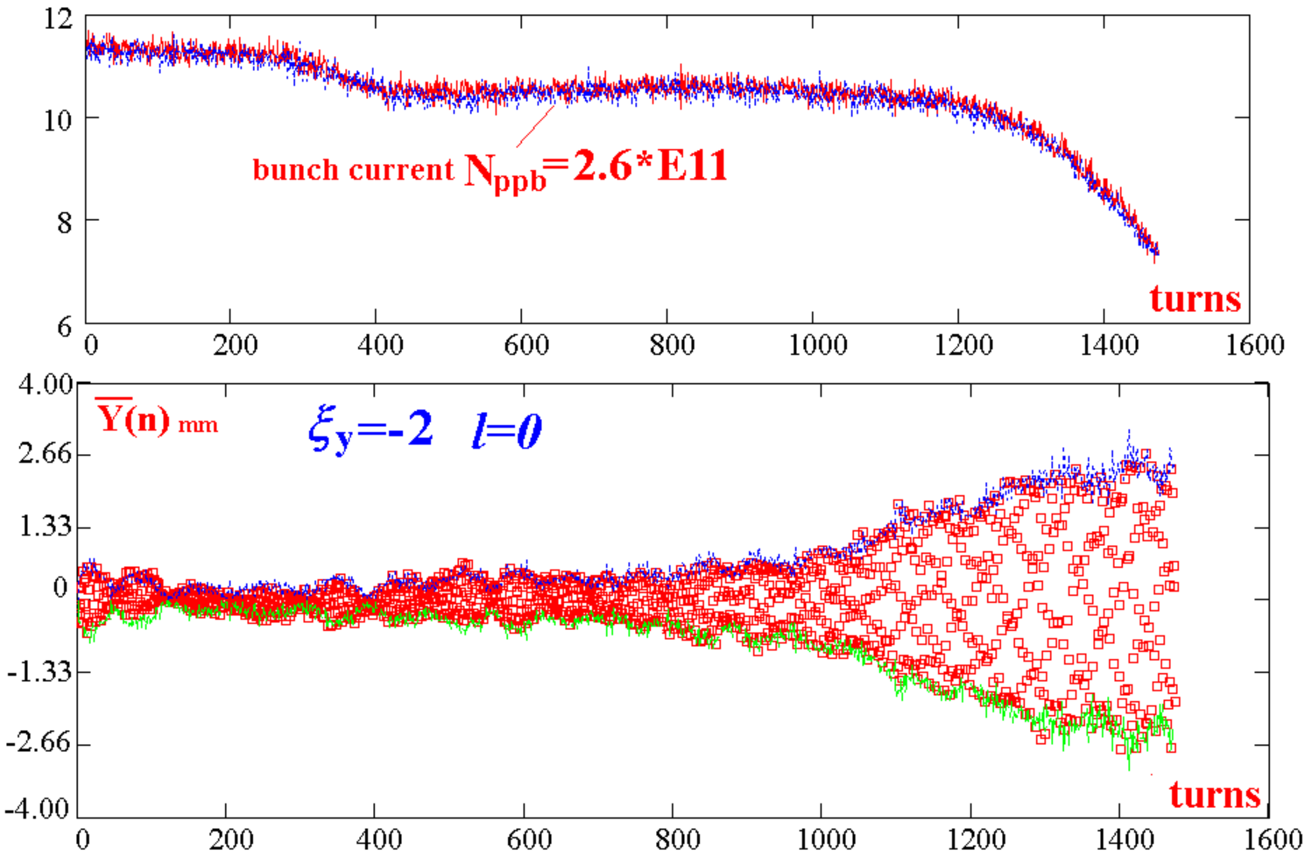


Fig.3 Developing of the coherent head-tail mode with monopole longitudinal configuration.

$$N \approx 2.6 \cdot 10^{11}, \xi_x \approx 6, \xi_y \approx -3, [\nu_x] = 0.5857, [\nu_y] = 0.5725$$

DEVELOPING OF THE COHERENT HEAD-TAIL MODE WITH MONOPOLE LONGITUDINAL CONFIGURATION.

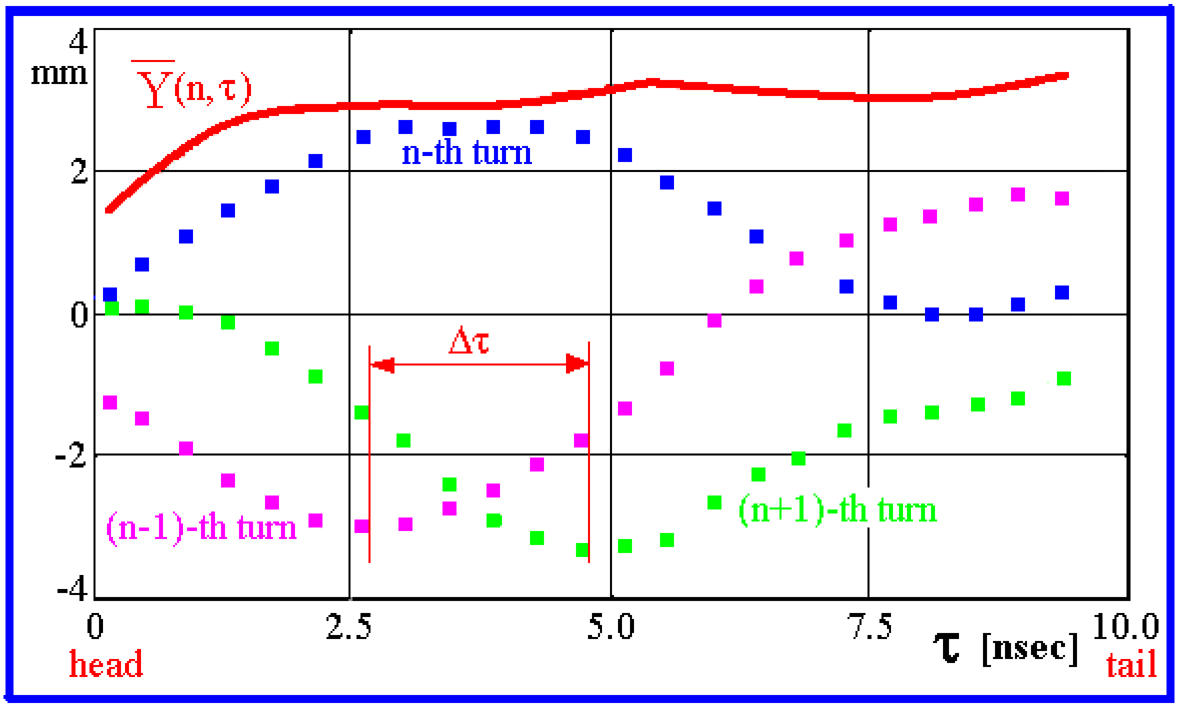


Vertical oscillation amplitude of the bunch centre vs. turns

At N_{ppb}=$2.6\cdot10^{11}$ and chromaticity values of $\xi_{x,\ y}\approx-2$, we identified that the coherent mode with l = 0 was developed with the coherent tune shift $\Delta\nu$=0.0011±0.0001 and the growth rate $1/\tau_0$=120±5 s^{-1}.

The coherent tune shift for the strongest mode is smaller than the synchrotron tune, $\Delta\nu\approx0.7\,\nu_s$. That classifies the instability as a weak head-tail.

HEAD-TAIL DYNAMICS OF THE COHERENT MODE WITH *l=0*



Transverse oscillations of the bunch dipole moment:

$$\overline{Y}(n,\tau) \propto \quad A_0 \cdot e^{t/\tau_0} \cdot \cos\left(\omega_\beta \cdot t + \chi \cdot \frac{\tau}{\tau_L}\right) \quad \{\tau = 0 \quad at\ the\ head\}$$

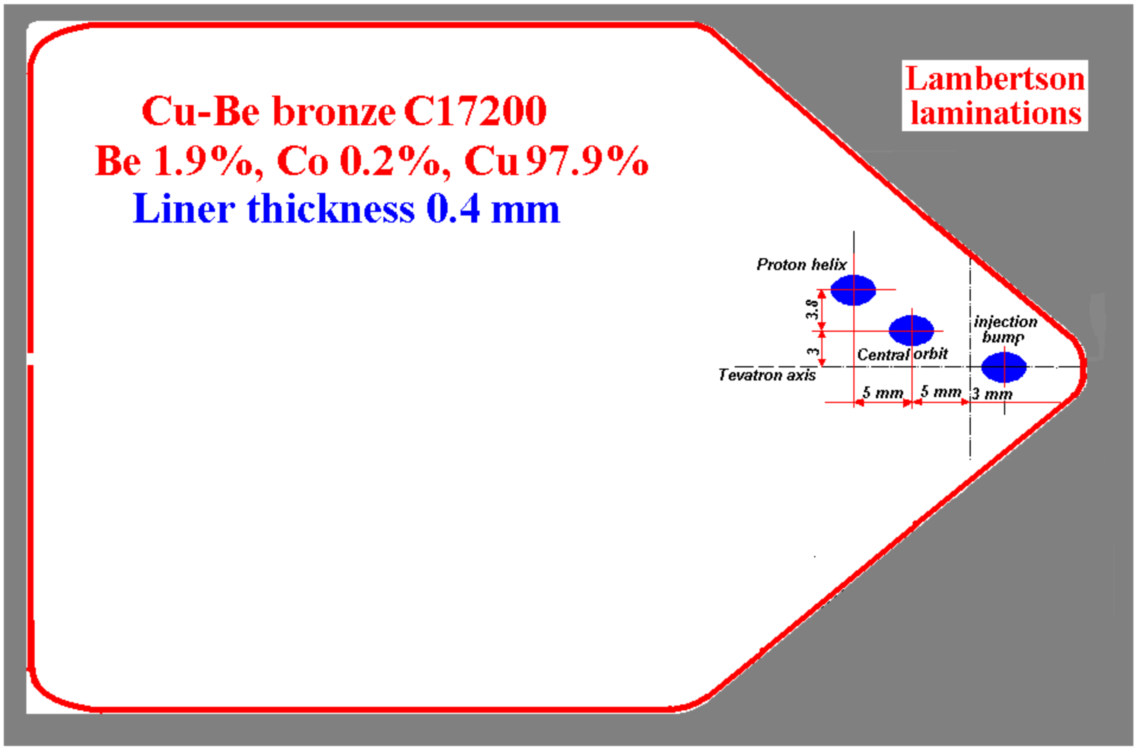
$\omega_\xi = \xi_y \cdot \omega_0 / \eta$ Betatron angular frequency shift due to chromaticity

$\chi = \xi_y \cdot \omega_0 \cdot \tau_L / \eta$ Total betatron phase shift from head to tail

$$\xi_y = \frac{(2\lfloor \nu_y \rfloor - 1)\eta}{f_0 \cdot \Delta\tau}$$

$$\xi_y = -3.2,\ \Delta\tau = 2.4\ nsec,\ \lfloor \nu_y \rfloor = 0.5725,\ \eta = 0.0028,\ f_0 = 47.7\ kHz$$

F0-LAMBERTSON LINER CONCEPTUAL DESIGN



Cu-Be bronze:

high electrical and thermal conductivity, high spring resistance

Liner thickness due to the aperture limitation: $t \le 0.5\,mm$

Head-Tail Instability-Single bunch effect: $f_{bunch} \cong 53\ MHz, \sigma_s \cong 0.9\ m$

Skin depths: $\delta_{CuBe} \approx 0.017\,mm, \delta_{Cu} \approx 0.009\,mm,\ \delta_{SS} \approx 0.06\,mm,\ t \approx 24\delta_{CuBe}$

$$\rho_{Cu-Be} = 6 \cdot 10^{-8}\ \Omega \cdot m \qquad \rho_{Cu} = 1.7 \cdot 10^{-8}\ \Omega \cdot m \qquad \rho_{SS} = 74 \cdot 10^{-8}\ \Omega \cdot m$$

Transverse Coupled Bunch Instability-Multi-bunch mode:

(driven by the resistive wall impedance)

Skin depths at the lowest negative betatron frequency $\omega_q = -(1 - \lfloor \nu_x \rfloor) \cdot \omega_0 \approx -0.4\,\omega_0$:

$$f_q = |\omega_q| / 2\pi \approx 19.1\,kHz \qquad \delta_{Cu-Be} \approx 0.9\,mm \qquad \delta_{SS} \approx 3.1\,mm, \quad t \approx 0.5\delta_{CuBe}$$

Liner screening effect for the Lambertson laminations at f_q=19 ***kHz***:

$Z^{\perp}(\textit{liner}) / Z^{\perp}(\textit{lamina}) << 1$ *(more than 10 times)*

CONCLUSION. F0-Lambertson magnet with the liner will not give any visible contribution to the transverse impedance budget.

TEVATRON TRANSVERSE RESISTIVE WALL IMPEDANCE BUDGET

The Tevatron stainless steel vacuum chamber is square in cross section with sides 2h=60 mm and rounded corners. The transverse impedance due to wall resistivity is:

$$Z_{\perp} = \left[1 + j\,\mathrm{sgn}(\omega)\right] \frac{c\rho C}{\pi\,\omega\delta\,h^3} \cdot F_g$$

$\delta = \sqrt{2\rho c / |\omega| Z_0}$ is the skin depth, $\rho = 7.4 \cdot 10^{-7}\ \Omega \cdot m$ is the resistivity of the SS wall, $Z_0 \approx 377\ \Omega$ is the free space impedance, $C = 2\pi R$, $R = 1000\,m$, $F_g = 1$.

For the frequency range up to wavelength of the order of the bunch length $f_b = \omega_b / 2\pi = c/\sigma_l \approx 53\ MHz$, n=1000, we have:

$$Z_{\perp} \approx \left[1 - j\right]\ 0.82\ M\Omega/m$$

Estimation of $\left(Z_{\perp}^{Tev}\right)_{tot}$ from measurements of the growth rate and coherent tune shift for head-tail mode with ***l=0*** (injection orbit bump at FO):

before January shut down:

$\frac{1}{\tau_0} \approx 130\ \mathrm{sec}^{-1} \Rightarrow$ lower limit of $Z_{\perp}^{Tev} \geq 4.5\ M\Omega/m$ (Landau damping is not included)

$$\Delta\nu_{l=0}^{coh} \approx 0.0013 \quad \Rightarrow \quad Z_{\perp}^{Tev} \approx \left[1 - j\right] 5.8\ M\Omega/m$$

after January shut down:

$\frac{1}{\tau_0} \approx 116\ \mathrm{sec}^{-1} \Rightarrow$ lower limit of $Z_{\perp}^{Tev} \geq 4.0\ M\Omega/m$ (Landau damping is not included)

$$\Delta\nu_{l=0}^{coh} \approx 0.0011 \quad \Rightarrow Z_{\perp}^{Tev} \approx \left[1 - j\right] 4.9\ M\Omega/m$$

C0-Lambertson magnet transverse impedance from the coherent tune shift measurements:

$$Z_{\perp}^{C0} \approx 5.8 M\Omega/m - 4.9 M\Omega/m = \left[1 - j\right] 0.9 M\Omega/m$$

Estimation of the C0-Lambertson magnet transverse impedance by Burov's formula (taken into account the stainless steel liner inside the magnet aperture): $Z_{\perp}^{C0} \approx \left[1 - j\right] 0.8 M\Omega/m$

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TEVATRON TRANSVERSE RESISTIVE WALL IMPEDANCE BUDGET

(continued)

Estimation of the upper limit for the F0-Lambertson magnet transverse impedance from the coherent tune shift measurements on the injection orbit:

$$Z_{\perp}^{F0} \leq 4.9\ M\Omega/m - 0.82 M\Omega/m \approx [1-j]4.1\ M\Omega/m$$

Estimation of the Tevatron total transverse impedance on central regular orbit:

$$Z_{\perp}^{Tev} \approx [1-j]2.4\ \ M\Omega/m$$

No Liner

Lambertson Cu-Be-liner transverse impedance is estimated in the semi-cylinder shape approximation with the effective radius b_{eff} and with F_g=0.5:

$$Z_{\perp}^{L} \approx [1-j]\cdot \frac{L_{tot}}{4\pi b_{eff}^{3}} \sqrt{\frac{2Z_0 c\rho}{\omega}} \approx [1-j]0.02 \quad M\Omega/m$$

No vacuum slots

in the frequency range of $f_b \approx c/2\pi\sigma_l \approx 53\ MHz$ and $\rho = 6\cdot10^{-8}\ \Omega\cdot m$, $b_{eff} \approx 8\,mm$, $L_{tot} \approx 12\,m$

Estimation of the Cu-Be-liner transverse impedance with 1 x 12.5 mm vacuum slots (2.5% of the liner total square):

$$Z_{\perp}^{L} \approx [1-j](0.025\cdot 4) = [1-j]0.1 \quad M\Omega/m$$

Expected Tevatron total transverse impedance on the central regular and proton injection orbits after liner inserting:

$$Z_{\perp}^{Tev} \approx [1-j]1\ M\Omega/m$$

CONCLUSION

F0-Lambertson magnet with the liner will not give any visible contribution to the Tevatron transverse impedance budget.

DAMPING OF THE HEAD-TAIL MODES

Universal method for damping the instability is to introduce a betatron frequency spread that is larger than the growth rates. Landau damping is effective when the following approximate conditions are satisfied:

$$\sqrt{\left(\delta\nu_{x,y}^{oct}\right)^2+\left(\delta\nu_{x,y}^{sc}\right)^2+\left(|l|\cdot\delta\nu_s\right)^2}\ \geq\left|\Delta\nu_{x,y}^{sc}-\Delta\nu_{x,y}^{coh}(l)\right|$$

$$\tau_{damp}\cong f_0\cdot(\delta\nu_{tot})_{HWHM}\ \approx 2.36 f_0(\delta\nu_{tot})_{RMS}\geq\ 1/\tau_l$$

***l* = *0*, ±1, ±2** are the longitudinal numbers of coherent head-tail modes

Synchrotron tunes: $\nu_{S0}=1.8\cdot10^{-3}, \delta\nu_s\approx0.22\cdot10^{-3}$, $\delta\nu_s\approx\nu_{S0}\cdot\frac{1}{8}\left(\omega_{RF}\cdot\langle\tau_L\rangle\right)^2$

For 3-D Gaussian bunch with $N_{ppb}=2.6*10^{11}$ (E=150 Gev):

Space charge linear tune shift: $\Delta\nu_x^{sc}=0.36\cdot10^{-3}\quad\Delta\nu_y^{sc}=0.7\cdot10^{-3}$

SC tune spread: $\delta\nu_{x,y}^{sc}\cong1/3\cdot\Delta\nu_{x,y}^{sc}, \delta\nu_x^{sc}\cong0.12\cdot10^{-3},\ \delta\nu_y^{sc}\cong0.23\cdot10^{-3}$

The two Tevatron regular octupole families are used to provide Landau damping for the head-tail modes:

$$OZD\left(n=12,\ \beta_x>\beta_y\right),\ OZD\left(m=24,\ \beta_y>\beta_x\right)$$

While the OZF-family has only 12 octupoles as compared with 24 units of the OZD-family but their effectiveness is quite comparable at same currents due to different Tevatron lattice parameters at octupole locations.

There are two sources of the octupole-driven tune spread:

$$\delta\nu^{\beta}_{x,y}=\frac{1}{16\,\pi\,B\rho}\left[J_{x,y}\sum_{1}^{n,m}\left(\overline{K}_3\beta^{2}_{x,y}\right)_{n,m}-2J_{y,x}\sum_{1}^{n,m}\left(\overline{K}_3\beta_x\beta_y\right)_{n,m}\right]$$

$$\delta\nu^{D}_{x,y}=\frac{\sigma^{2}_{\Delta p/p}}{16\,\pi\,B\rho}\sum_{1}^{n,m}\left(\overline{K}_3\,\beta_{x,y}\,D^{2}_{x}\right)_{n,m}$$

$J_{x,y}=a^{2}_{x,y}\big/\beta_{x,y}$ are the single particle Courant-Snyder invariants.

$\overline{K}_3(n,m)=\mathcal{J}_{n,m}(Amps)\cdot\int_0^{L_0}\frac{\partial^3 B_y}{\partial x^3}ds/1\,Amp=616\cdot\mathcal{J}_{n,m}\quad\left[T/m^2\right]$ are the normalized octupole strengths with $\mathcal{J}_n,\mathcal{J}_m$ as the OZF- and OZD-family octupole currents.

The betatron tune spread generated by octupoles depends dominantly on momentum spread of the beam due to dispersion function at the octupole locations.

l=1 COHERENT MODE DAMPING on CENTRAL ORBIT.

Required currents as $\mathcal{J}_{OZD}\approx 4.2\,A$ and $\mathcal{J}_{OZF}=0$ with the estimated tune spreads due to the octupoles as: $\left\langle\delta\nu^{Oct}_{y}\right\rangle\approx 2.8\cdot 10^{-4}$, $\left\langle\delta\nu^{Oct}_{x}\right\rangle\approx 1\cdot 10^{-4}$.

Stabilizing betatron tune spreads for modes with ***l=1*** are:

$$\left\langle\delta\nu_y\right\rangle_{tot}\approx 4.2\cdot 10^{-4}\;>\;\left|\Delta\nu^{sc}_{y}-\Delta\nu^{coh}_{y}(l=1)\right|\cong 3.5\cdot 10^{-4}\;>\;\left\langle\delta\nu_s\right\rangle$$

$$\left\langle\delta\nu_s\right\rangle\approx 2.2\cdot 10^{-4}\;>\;\left|\Delta\nu^{sc}_{x}-\Delta\nu^{coh}_{x}(l=1)\right|\cong 1\cdot 10^{-4}$$

COHERENT MODE DAMPING AT NEGATIVE CHROMATICITY

At the chromaticities of $\xi_{x,y} \cong -2$ the coherent modes ***l=0*** has been stabilized at $\mathcal{J}_{OZD} \approx 5A$ and $\mathcal{J}_{OZF} \approx 2A$ with the estimated tune spreads due to the octupoles as: $\langle \delta\nu_y^{Oct} \rangle \approx 5.2 \cdot 10^{-4}$, $\langle \delta\nu_x^{Oct} \rangle \approx 4.1 \cdot 10^{-4}$.

Stabilizing betatron tune spreads for the head-tail modes with ***l=0*** are:

$$\langle \delta\nu_y \rangle_{tot} \approx 5.7 \cdot 10^{-4} \; > \; \left| \Delta\nu_y^{sc} - \Delta\nu_y^{coh}(l=0) \right| \cong 2 \cdot 10^{-4}$$

$$\langle \delta\nu_x \rangle_{tot} \approx 4.3 \cdot 10^{-4} \; > \; \left| \Delta\nu_x^{sc} - \Delta\nu_x^{coh}(l=0) \right| \cong 1 \cdot 10^{-4}$$

The widths of betatron spectra measured by Schottky monitor are in a reasonable agreement with this calculation taking into account the contributions from the synchrotron and direct space-charge tune spreads.

Transverse impedance and growth rate on central orbit are estimated as:

$$\frac{1}{\tau_0} \propto \mathrm{Re}\left(Z_\perp^{Tev}\right)\cdot\chi = \mathrm{Re}\left(Z_\perp^{Tev}\right)\cdot\xi_{x,y}\cdot\omega_0\cdot\tau_L / \eta \qquad \chi \le 1$$

$$Z_\perp^{Tev} \approx [1-j]\,2.4\ M\Omega/m \qquad \Rightarrow \qquad 1/\tau_0 \approx 40 \pm 3\,\mathrm{sec}^{-1} \quad (\xi_{x,y} \approx -2)$$

$$\tau_{damp} \cong f_0 \cdot (\delta\nu_{tot})_{HWHM} \approx 2.36 f_0 (\delta\nu_{tot})_{RMS} \ge 1/\tau_{l=0}$$

$$\tau_{dy} \approx 2.36 \cdot 47.7 \cdot 10^3 \cdot 0.57 \cdot 10^{-3} \approx 64\, s^{-1}, \qquad \tau_{dx} \approx 2.36\, f_0 \langle \delta\nu_x \rangle_{rms} \approx 48\, s^{-1}$$

The octupole cubic non-linearity has a positive sign: $\frac{\partial \nu_{x,y}}{\partial\left(a_{x,y}^2\right)} > 0$

This is important from dynamic aperture point of view since the vertical tune is slightly above the resonance $\nu_y = 4/7$.

It is "right" sign to minimize the octupole strengths of the OZD-family in consequence of:

$$\left(\Delta\nu_y^{sc} - \Delta\nu_y^{coh}(l=0)\right) > 0$$

OCTUPOLE EFFECTS ON HELICAL ORBIT

Tevatron lattice parameters and helix beam orbit offsets are used from file "v3h01v2" (MAD format). $E=150 Gev, (B\rho)=500\, T\cdot m$

Computer simulation of the octupole effects has been performed by Lebedev's computer code "OPTIM"

LINEAR BETATRON TUNE SHIFT

The octupoles result in a betatron tune linear shift for particles with small oscillation amplitudes on the helical beam orbit with respect to the central orbit:

$$\Delta\nu_{x,y}=\frac{1}{8\pi\cdot(B\rho)}\left[\mathcal{J}_{OZF}\cdot\sum_{1}^{n=12}\left(\overline{K}_3\beta_{x,y}\left(\Delta x_0^2-\Delta y_0^2\right)\right)_n+\mathcal{J}_{OZD}\cdot\sum_{1}^{m=24}\left(\overline{K}_3\beta_{x,y}\left(\Delta x_0^2-\Delta y_0^2\right)\right)_m\right].$$

$\Delta x_0, \Delta y_0$ are the horizontal and vertical beam orbit offsets at octupole locations due to the helical orbit.

It is assumed that $\Delta x_0(P)=-\Delta x_0(\overline{P}),\ \Delta y_0(P)=-\Delta y_0(\overline{P})$ with respect to the octupole axis.

$\Delta\nu \propto \left(\Delta x_0^2-\Delta y_0^2\right)$ for P- and $\vec{P}$-helixes are the same.

For the Octupole Settings: $\mathcal{J}_{OZF}=2\ Amps, \mathcal{J}_{OZD}=5\ Amps$

Estimated betatron tune shifts: $\Delta\nu_x=-0.0021,\quad \Delta\nu_y=+0.0042$

Measured betatron tune shifts: $\Delta\nu_x=-0.003,\quad \Delta\nu_y=+0.005$

With the octupoles on, the Open Helix Ramp was used to compensate these betatron tune shifts by Tevatron regular tune correctors.

LINEAR CHROMATICITY SPLITTING

$$\Delta\xi_{x,y} = \frac{1}{4\pi(B\rho)}\left[\mathcal{J}_{OZF}\sum_{1}^{n=12}\left(\overline{K}_3\beta_{x,y}\left(\Delta x_0 D_x - \Delta y_0 D_y\right)\right)_n + \mathcal{J}_{OZD}\sum_{1}^{m=24}\left(\overline{K}_3\beta_{x,y}\left(\Delta x_0 D_x - \Delta y_0 D_y\right)\right)_m\right]$$

In approximation $D_y \ll D_x$ **,** the chromaticity change $\Delta\xi_{x,y} \propto \Delta x_o D_x$

Since $\Delta x_o(\mathrm{P}) = -\Delta x_o(\overline{\mathrm{P}})$, **Consequently** $\Rightarrow \Delta\xi_{x,y}(\mathrm{P}) = -\Delta\xi_{x,y}(\overline{\mathrm{P}})$

For the Octupole Settings: $\mathcal{J}_{OZF} = 2\ Amps$, $\mathcal{J}_{OZD} = 5\ Amps$

Measured chromaticity changes at transition from the central orbit to proton helix with the octupole on:

$$\Delta\xi_x \approx -2 \quad \Delta\xi_y \approx 0$$

Computer simulation by OPTIM: $\Delta\xi_x = -1.87 \quad \Delta\xi_y \approx +3.8$

There is strong sensitivity to the beam orbit distortions around machine!

For instance, A42 octupole horizontal offset (or central orbit with respect to the octupole position) by Δx=5 mm results in **$\Delta\xi_x = \pm 1.3$ at I_{OZF}=5 Amps.**

CONCLUSION

Introducing Feeddown Octupoles with individual Power Supplies can solve the problem of the chromaticity split between the proton and antiproton helixes.

BETATRON COUPLING

Skew-quadrupole gradient of octupole on the helical orbit is:

$$\frac{\partial B_y}{\partial y} = \frac{\partial B_x}{\partial x} = -\frac{\partial^3 B_y}{\partial x^3} \Delta x_0 \Delta y_0$$

Since $\Delta x_0(P) = -\Delta x_0(\overline{P})$, $\Delta y_0(P) = -\Delta y_0(\overline{P})$ the product $\Delta x_0 \Delta y_0$ has the same sign for the P and $\overline{P}$ helical orbits at same octupole location. It means that change of the betatron coupling for both orbits will be symmetric with respect to the central orbit and can be easily compensated by regular skew-quadrupoles.

Computer simulation of betatron coupling correction on the helical orbits

The most optimal betatron coupling correction is achieved when the SQ-skew quadrupole family is used.
to reduce to a minimum the betatron coupling on both helical orbits:
Current SQ: I_{SQ}=-2.873 *Amps* $\Rightarrow I_{SQ}$=-3.01 *Amps*, ΔI_{SQ}=-0.137

Betatron tune split minimum : $|\nu_1 - \nu_2| \approx 0.0032$

Experiment on Tevatron**:** ΔI_{SQ}=-0.197 Amps

TEVATRON OCTUPOLE FAMILIES

PROPOSAL

Four octupole families with individual Power Supplies can provide Landau damping and lattice chromaticity symmetry for the proton and antiproton helical orbits.

Octupole Families	Octupole locations and polarities
Vertical Chromaticity Feeddown Octupoles 12 Units T: ???	A23(+), A27(-), B27(-), B33(+),C23(-), C27(+) D27(-), D33(+), E23(-), E27(+), F33(-),F37(+)
DEFOCUSING OCTUPOLES OZD 24 Units	**Defocusing Octupoles OZD are sorted into two independent groups:** "Vertical Chromaticity Feeddown Octupoles" "Betatron Tune Spread Octupoles"
Betatron Tune Spread Octupoles 12 Units T:OZD	A33(+), A37(+), B23(+), B37(+), C33(+),C37(+) D23(+), D37(+), E33(+), E37(+), F23(+), F27(+)
Betatron Tune Spread Octupoles 12 Units T:OZF	A36(+), A42(+), B36(+), B42(+), C36(+), C42(+) D36(+), D42(+), E36(+), E42(+), F36(+), F42(+)
Horizontal Chromaticity Feeddown Octupoles 15 Units T: O39S	B19(+), B26(-), B28(-), C17(+), C19(+) C26(-), C28(+), E17(+), E19(off), E26(-) E28(+), F17(-), F19(-), F26(+), F28(-)

SUMMARY

It was predicted and it has been shown experimentally that F0-Lambertson magnet gives the dominant contribution to the Tevatron transverse impedance budget on central orbit and it is responsible for excitation of higher order head tail modes at the injection (due to the injection F0- local beam orbit bump).

The driving mechanism is the short-range wake fields induced through the resistive wall impedance and the head-tail instability is a single bunch effect.

Inserting the 0.4-mm thick Cu-Be bronze liner will result in:

- **stabilization of the higher order head-tail modes at positive chromaticities;**
- **significant (2.5 times) decreasing of the growth rate for coherent mode with the monopole longitudinal configuration at negative chromaticities; simple requirements for Landau damping at any mode of Tevatron operation;**
- **the same head-tail stability conditions on the central, helical, and injection orbits;**

Operation at zero chromaticity and introducing Landau damping by octupoles:

- **dynamic aperture and beam life time increasing;**
- **growth of the colliding beam intensities.**

As a result, the peak and integrated luminosity can be increased.